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Modelling the impacts of a water trading scheme on freshwater habitats

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ABSTRACT

Water trading is aimed at allocating abstracted water more fairly amongst stakeholders, however the direct effect this has on the natural flow regime and consequently on freshwater ecosystems has not been investigated in depth. This paper proposes a novel modelling methodology bringing together habitat and water trading numerical models with statistical models to show how water trading may affect three freshwater species: Fish (*Salmo Trutta*), Macrophytes (*Ranunculus Fluitans*) and Benthic macroinvertebrates (*Ephemeroptera Beraeidae*). Results indicated that trading regimes with environmental constraints to protect the environment had little effect on habitat availability however; trading without such requirements had an impact. Lower habitat suitability scores were apparent under the trading scenarios with lower levels of suitable habitat occurring. However putting these results within the context of natural variability, whilst there was a change in habitat availability, this change is within the natural flow/habitat variance and therefore water trading in the studied catchment is unlikely to impact the overall habitat availability.

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1. Introduction

Anthropogenic pressures impact freshwater ecosystems around the world. Over-abstraction, land use change and hydropower are just some of the pressures which impact natural flow regimes and exacerbate water scarcity issues (Poff et al., 1997). Water scarcity, as a result of anthropogenic pressures, not only causes direct implications to human populations but can also be the driver of many stressors on river ecosystems. It can result in intermittent flows which impact hydrological connectivity, biodiversity, water quality, pollution, and river ecosystem functioning (Blasco et al., 2015). Water trading initiatives have been developed around the world in an attempt to more fairly allocate water resources and simultaneously to protect water for the environment and species (Johansson et al., 2002; Bjornlund, 2003; Quesne et al., 2007; Erfani et al., 2015).

Water trading is the act of transferring the rights of a license to abstract water (e.g. for drinking water supply or agricultural purposes) from one user to another for the benefit of both users. Where each licence has a set of associated rules which may state a volume of water for abstraction (over a season or through the year) and may also have a flow below which no abstraction can take place in order to protect the environment (known in the UK as a Hands off Flow (Erfani et al., 2015)). Each licence can be fully or partially utilized in any year. In a change to historical water abstraction regulation, in the last few years water trading has been promoted in England and Wales (U.K) as a way to alleviate water scarcity issues, particularly in drought prone areas such as the South East. Water trading has been permitted in England for around the past 10 years, however barriers to this trading have limited the number of trades (Lumbroso et al., 2014). The recently implemented Water Act 2014, derived from the Water White Paper (2010), aims to implement a more efficient use of the water that is abstracted. These aims, alongside the EU Water Framework Directive, means that water trading of abstraction licences at the catchment scale is likely to become more frequent in the future.

Modelling water markets, and thus water trading to investigate its effect on water flows in a river is a significant challenge. Hydroeconomic models (Harou et al., 2009), until recently, have struggled with the challenge of representing the interaction of wide ranging actors and institutions with the highly variable spatial and temporal hydrological environment (Erfani et al., 2014). Erfani et al. (2014, 2015), proposed a model which simulates the short-term (spot market) trading behaviour between individual licence holders and its effect on the hydrological regime. The approach uses pair-wise trading by licence holders, and a single objective function which maximises the regional economic benefits at each time

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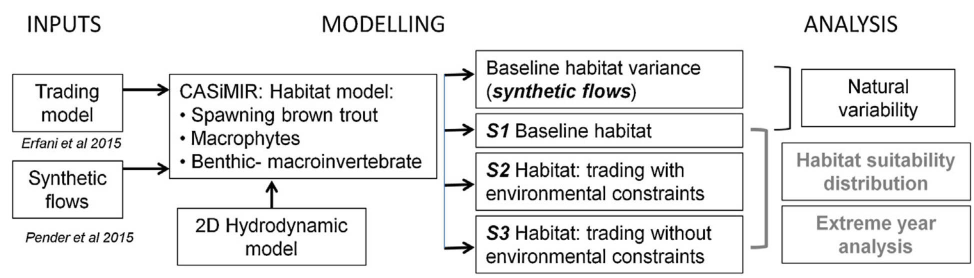

Fig. 1. Modelling methodology.

step, allowing trading with downstream abstractors. Different constraints on behaviour can be built into the model, for example different environmental flow (hands off flow) requirements can be tested to explore the flexibility of the environment (Erfani et al., 2015). However this stops short of investigating the effect of the potential changes in the hydrological regimes on in-stream habitat, delivering only the changed flow regimes resulting from the water market.

Water trading will affect the existing flow dynamics of catchments, as water will be abstracted with a different temporal and spatial signal, thereby changing and potentially reducing flows in particular reaches of the river at critical times. This inevitably has an effect on habitat availability for aquatic species. Currently there has been little or no investigation into how water markets may impact the environment, nor indeed to what extent the environment could be flexible to allow more trades to occur. The need to address the consequences of trading to aquatic species is of great importance in order to protect vital ecosystem services. Habitat models are well-established and successful tools to predict how changes in flow affects available habitat for freshwater species (Dunbar et al., 2007). These models provide structure to investigate interacting hydraulic processes and their influence on habitat distribution (Dunbar et al., 2012; Garbe et al., 2016). However several criticisms can be levelled at these models; firstly the input methods used (e.g. habitat suitability curves or fuzzy logic) can produce different results (Boavida et al., 2014), and secondly only hydraulic components are captured by the models while it is recognised that other biotic and abiotic factors such as refugia and food availability also play an important part in available habitat (Orth 1987). Garbe et al. (2016), proposed a method to address these criticisms by combining a series of habitat models of different indicators in order to understand a fuller picture of habitat not constrained to hydraulic parameters only. Consequently by using this approach to combat these criticisms, habitat models provide a very accessible and appropriate platform to assess changing habitat availability as a result of water licence trading.

Finally, a deterministic approach to habitat modelling provides significant insights for habitat distribution (Garbe et al., 2016; Muñoz-Mas et al., 2012), however it provides only one realisation of the impact to future habitats. Consequently to understand any potential habitat impacts holistically, and place that change within the context of natural variability, any assessment must consider more than one realisation of the flow regime. This requires a time series of river flows. Given that many UK rivers have gauges affording up to 50 years of recorded flow data, there is a need to generate synthetic streamflow series. Commonly this is completed using rainfall runoff models, however statistical approaches (e.g. Augustin et al., 2008; Can et al., 2012) offer a powerful alternative. Pender et al. (2016a) proposed a method which uses a hidden Markov model (HMM) linked to an extreme value model (Generalised Pareto) to create synthetic flow series from gauged data. The method has been tested across UK catchments, as well as used to investigate the sensitivity of flood inundation extents to morphological change (Pender et al., 2016b). Hence this provides a UK appropriate synthetic river flow generator which can be used to create statistically similar flow series in order to test the natural variability of in-stream habitat.

The aim of this paper is therefore to combine these novel advances to create a bespoke framework to investigate the potential impact on in-stream aquatic habitat that a water market (and the subsequent trades) may have.

2. Methods

The novel methodology proposed in this paper brings together recent advancements in a number of modelling spheres to create a method which allows the impacts of water trading impacts on in-stream habitat to be quantified.

Fig. 1 sets out the proposed modelling framework. At the heart of the methodology lies the combined habitat modelling approach proposed by Garbe et al. (2016). As input to this a Water Trading model following Erfani et al. (2014) simulates trading on the catchment and the subsequent impact to the flow regime; alongside synthetic flows generated using the method proposed by Pender et al. (2016a) in order to place the changes in the context of natural variability. The setup, simulation and coupling of each of these models for the case study catchment is described below.

2.1. Case study and site location

Chalk streams are globally rare and provide very important in-stream habitat. Internationally there are around 200 chalk streams, of which 85% are located in South East England, an area of the UK where rivers face significant anthropogenic pressures as a result of abstraction. Given their importance in terms of habitat this study focussed on the River Nar, a chalk stream in Norfolk in the South-East of England. The river Nar's distinctive progression from a chalk to fen (wetland) type habitat has resulted in a Site of Special Scientific Interest (SSSI) designation, with the chalk reach being particularly sensitive to low flows, and thus over abstraction. Despite its status of high conservation value, it has been historically modified along most of its length. Abstraction, diffuse pollution and the legacy of channel modifications all contribute to pressures on the ecology of the river. Abstraction is a significant problem in the river Nar; the lower river (downstream of Narborough) is classified as 'over-licensed', whilst the upper river is classified as 'over-abstracted' by the Environment Agency (EA) (EA, 2005). There are numerous abstractors along the river, the most significant of which is a large Drinking Water Supply company. Other abstractors include agricultural and fisheries stakeholders. During the most extreme hydrological drought year on record at Marham (1991) the river failed its flow targets as set for the Water Framework Directive (WFD) which reflect the sensitivity of ecology in the river (Norfolk Rivers Trust, 2013). This study catchment was chosen to demonstrate the method based on its designation of 'over abstracted', its potential for trading amongst users (Whaley and Weatherhead,

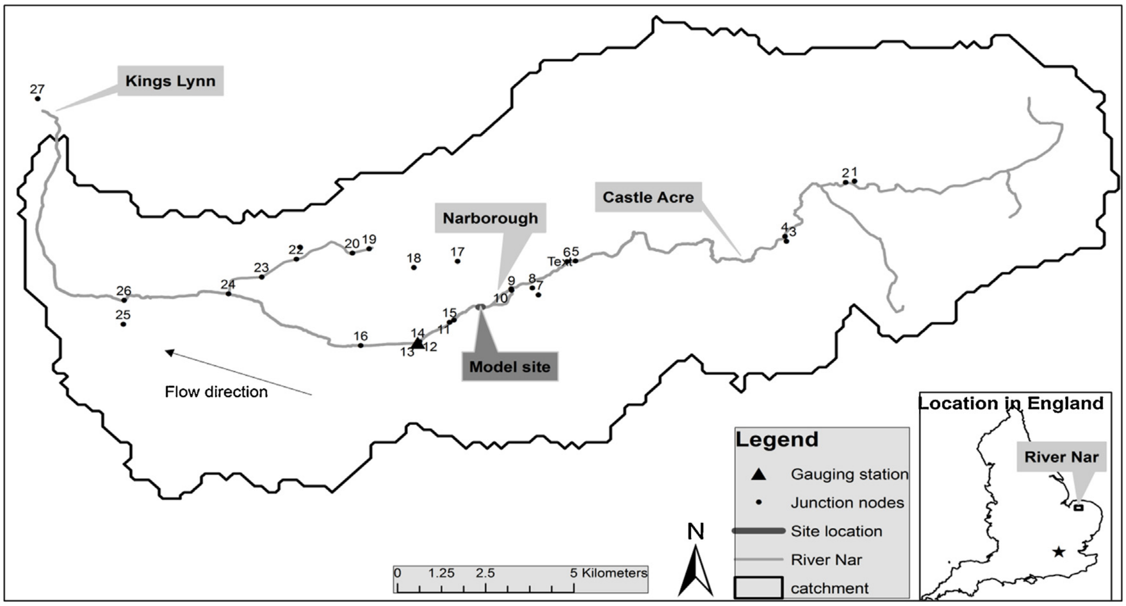

Fig. 2. River Nar catchment map, indicating study area and trading model nodes.

2014), its sensitivity to low flows and its environmental sensitivity (Garbe et al., 2016).

The river is approximately 42 km in length with one gauging station at Marham, situated at around the dividing point between chalk and fen sections (Fig. 2). The mean flow at Marham is 1.14 m^3/s. The highest and lowest recorded flows between 1953 and 2014 are 7.8 m^3/s and 0.14 m^3/s respectively. High (Q_{10}) and low (Q_{90}) flow parameters for this period are 2.02 m^3/s (1.87 m^3/s at the model site) and 0.47 m^3/s (0.3 m^3/s) respectively. Due to the underlying chalk, the river has a high Base flow index (BFI), which is typical of pure chalk streams (Norfolk Rivers Trust, 2013). The river is host to a diverse range of aquatic species. Brown trout (*Salmo Trutta*) are of particular importance in the river and are considered highly valuable by the local fisherman. The river provides good habitat for a large range of benthic macroinvertebrates and a rich abundance of chalk stream macrophytes such as water crowfoot (*Ranunculus*). A study reach of 500 m was chosen near the middle of the river, approximately 2.5 km upstream of the gauge, for the research given its importance for spawning fish (Fig. 2).

2.2. Habitat model development

In order to examine the habitat of spawning brown trout (*Salmo Trutta*) in detail, other indicator species were included in the model, to understand their available refugia (macrophytes (*Ranunculus Fluitans*)) and food sources (benthic macroinvertebrates (BMI) (*Ephemeroptera Beraeidae*)) as well as their hydraulic habitat (Garbe et al. (2016)). This allows a fuller picture of the ecosystem dynamics in the study reach. *Salmo Trutta* and *Ranunculus Fluitans* were specifically chosen due to their abundance in the case study river and due to their importance specifically to chalk streams. *Ephemeroptera Beraeidae* were chosen to represent benthic macroinvertebrates due to their importance as a food source to fish. This follows the approach proposed by Garbe et al. (2016), where the specific indicator is taken to be brown trout (*Salmo Trutta*), but that its dependents (food Source: (*benthic macroinvertebrates*) (*Ephemeroptera Beraeidae*) and in-stream refuge (macrophytes) (*Ranunculus Fluitans*)) are also included in the analysis.

The habitat models used are 2D CASiMiR models which require 2D hydrodynamic information on the flow conditions in the river.

Table 1
Cover and substrate values.

Substrate types	Index (–)	Cover types	Index (–)
Organic material, detritus	0	No cover	0
Silt, clay, loam	1	Aquatic plants	1
Sand <2 mm	2	Stones/detritus	2
Fine gravel 2–6 mm	3	Roots	3
Medium gravel 6–20 mm	4	Deadwood	4
Large gravel 2–6 cm	5	Wet branches	5
Small stones 6–12 cm	6	Dry branches	6
Large stones 12–20 cm	7	Floating macrophytes	7
Boulders > 20 cm	8	Turbulence	8
Rock	9	Undercut banks	9
		Overhanging grass	10

Cover and substrate values were incorporated based on field observations in spring (May) 2014. The substrate values used were based on the Wentworth scale and the cover values were as specified in CASiMiR (Bovee 1986) (Table 1). Hydrodynamic information on the flows in the study reach were extracted from a 2D hydraulic model (TUFLOW). For habitat suitability data, fuzzy logic rules were used to expresses non-linear relationships between ecological variables in a transparent manner (Muñoz-Mas et al., 2012). The biotic variables used were; water depth, velocity, substrate and cover (i.e. in-stream vegetation). These variables are generally considered the most important microhabitat variables in determining habitat selection (Louhi et al., 2008). Fuzzy rule and set determination for each species is described below, final fuzzy rules and sets are presented in Appendices A and B respectively.

2.2.1. Hydraulic model

The 2D hydrodynamic model was built of the reach, using TUFLOW. This provided hydraulic input (depth, velocity and flow) for the CASiMiR models. Topographic data based on LiDAR (2012) and survey data (river channels (2013)) was used to build the mesh. Gauged flows from Marham were available for the upstream boundary. Calibration for in-bank flows only was sufficient for this study. Model calibration was completed using measured water levels for known flows surveyed in May 2013. The resulting calibration suggested a manning's n of 0.05, which gave water levels (+/–) 0.2 m through the reach.

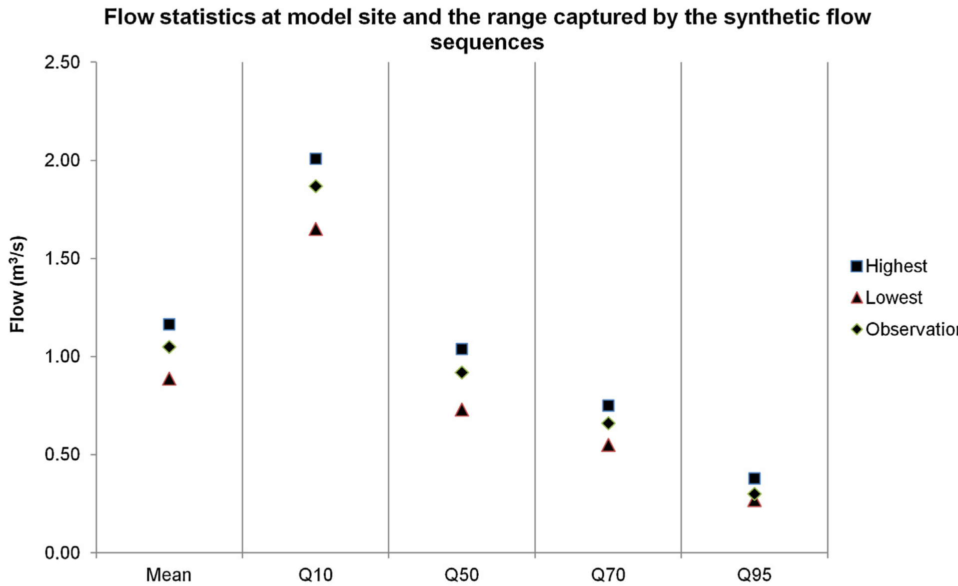

Fig. 3. Synthetic flow statistics.

*2.2.2. Spawning brown trout (*Salmo trutta*)*

Fuzzy rules and sets for spawning brown trout were derived based on literature (Armstrong et al., 2003; Louhi et al., 2008; Garbe et al., 2016). The relationship between spawning brown trout and flow conditions has been well researched. Generally low velocities (0.2 m/s–0.55 m/s) and low depths (0.15 m–0.45 m) are most preferred (Louhi et al., 2008). Whilst cover is important for spawning brown trout (Armstrong et al., 2003), it was not included as a variable in the fuzzy rules as it is considered in the modelling methodology through the use of macrophytes as an indicator (Garbe et al., 2016). Substrate is known to be an important factor for spawning brown trout (Armstrong et al., 2003), and must be unconsolidated hence medium gravel was considered the preferable substrate.

*2.2.3. Macrophytes (*Ranunculus fluitans*)*

Fuzzy rules for macrophytes (*Ranunculus Fluitans*) were validated to the river based on field surveys and literature (Dawson, 1973; Spink, 1992; Garbe et al., 2016). A preferential substrate of gravel was chosen rather than silt and sand, based on field survey results (Garbe et al., 2016) which indicated most *Ranunculus Fluitans* in the Nar is found in medium substrates and not in silt or sand.

*2.2.4. Benthic macroinvertebrates (*Ephemeroptera beraeidae*)*

The benthic macroinvertebrates data (*Ephemeroptera Beraeidae*) were developed based on fuzzy rules for the family of mayfly. In the CASiMiR model, velocity, substrate and FST hemisphere curves define the mayfly habitat (Kopecki, 2000). FST values (number depicting hydraulic stress acting on Benthic macroinvertebrate species) were provided from previous studies (Kopecki, 2008; Garbe et al., 2016) and preferences for depth, velocity and substrate were verified using literature (Jowett, 1990; Dewson et al., 2007; Kopecki, 2008).

Medium depth was established as preferred and velocities over 0.75 m/s. Medium substrate (under an index of 4-Table 1) provides poor habitat, and high substrate (over an index of 4-Table 1) provides good habitat. FST numbers for *Ephemeroptera Beraeidae* are shown in the FST fuzzy set in Appendix B.

2.3. Flow regime scenarios

The habitat models were run using different input scenarios; those that represent water trading as well as those which represent natural variability. Two different models were used:

- Water trading model: a hydro-economic model capable of representing water markets in a catchment, and
- Synthetic flow generator: a statistical model capable of creating statistically similar flow series.

An historical 32-year period (1980–2011) was chosen as the period of comparison as this captured the period of gauged low flow in the catchment. The existing flow time series recorded at Marham gauge was used as the baseline/existing flow sequence. All other sequences are either perturbed versions of this (trading scenarios resulting from the trading models), or synthetic versions of this (synthetic flow series resulting from the statistical models which capture the same statistical properties and extremes as this baseline series) (Fig. 1).

2.3.1. Water trading model

The water trading model was built using GAMS (General Algebraic Modelling System) software which used economic optimisation to simulate and track pair-wise water market transactions between individual water users following Erfani et al. (2014) and Erfani et al. (2015). The model is used to simulate short-term (spot market) trading amongst individual water rights holders, where the trades are driven by an economic demand curve that represent each abstractor's water demand, which is time varying. A single-objective function means the model implements those trades which maximise regional economic benefits at each time step (in this case a week). The model assumes that users with a higher willingness to pay will buy water from abstractors with lower marginal benefits if the transaction costs do not discourage it. The individual preferences of specific abstractors to trade or not trade with other users are accounted for through detailed user-to-user transaction costs or rules imposed as constraints in the mathematical program (Erfani et al., 2014). For most abstractors, water use is not fully consumptive so some water is returned to the river as return flow. The sum of volumes of water abstracted and sold cannot exceed their annual and weekly license allocations

Table 2
Overview of the attributes of the synthetic flow sequences at the model site.

	Max	Min	Median	Mean	Q10	Q50	Q70	Q95
Observations								
Site	6.71	0.12	0.92	1.05	1.87	0.92	0.66	0.30
Synthetic Flows								
1	6.28	0.12	0.80	0.93	1.66	0.80	0.58	0.28
2	7.22	0.12	0.93	1.05	1.92	0.93	0.63	0.29
3	6.44	0.12	0.73	0.89	1.65	0.73	0.55	0.28
4	8.58	0.12	0.87	0.99	1.78	0.87	0.63	0.30
5	7.82	0.12	0.91	1.02	1.77	0.91	0.66	0.31
6	6.99	0.13	0.88	1.01	1.81	0.88	0.65	0.30
7	8.99	0.12	0.89	1.02	1.80	0.89	0.66	0.31
8	6.15	0.12	0.97	1.07	1.89	0.97	0.70	0.31
9	7.96	0.12	0.85	1.00	1.82	0.85	0.58	0.28
10	9.02	0.12	0.99	1.12	1.99	0.99	0.71	0.31
11	6.18	0.13	0.87	1.02	1.82	0.87	0.65	0.31
12	8.44	0.13	0.92	1.01	1.72	0.92	0.67	0.33
13	8.74	0.12	0.90	1.02	1.78	0.90	0.64	0.29
14	6.45	0.12	0.76	0.95	1.80	0.76	0.56	0.27
15	8.86	0.12	0.87	1.02	1.86	0.87	0.63	0.28
16	8.51	0.12	0.84	0.97	1.74	0.84	0.61	0.30
17	5.47	0.12	0.83	0.95	1.67	0.83	0.61	0.29
18	6.48	0.13	0.81	0.94	1.69	0.81	0.59	0.28
19	7.79	0.12	0.87	1.02	1.90	0.87	0.62	0.30
20	6.99	0.12	1.04	1.16	2.01	1.04	0.75	0.38

Table 3
(a) Suitability scales for HHS total habitat availability. (b) – Suitability scales for spatial habitat availability (SI).

(a) Suitability scale	Corresponding HHS values (–)
Very good suitability	0.81–1
Good suitability	0.61–0.8
Moderate suitability	0.41–0.6
Poor suitability	0.21–0.4
Very poor suitability	0–0.2

(b) Suitability scale	Corresponding SI values (–)
Highly suitable	0.81–1
Suitable	0.61–0.8
Moderate suitability	0.41–0.6
Unsuitable	0.21–0.4
Highly unsuitable	0–0.2

(Erfani et al., 2014, 2015). Trades are optimised at each timestep, and thus a decision to trade or not is made at this temporal resolution.

The river network was modelled as a series of 27 nodes and conveyance links representing: demands, storage reservoirs, junctions, river reaches i.e. tributaries, these created a connection matrix for the river and abstractors (see Fig. 2) for node locations on the Nar. The abstractors ranged from large Water Company, fish farms to individual farmers, each with an individual licence (e.g. water volume annual/seasonal and associated environmental constraint). For each node at each time step, economic benefit functions that quantify economic gains are provided. The objective function is the sum of economic benefits from water use across all users in each individual time step, this objective function identifies trades that make sense economically whilst adhering to constraints. Environmental constraints were included in the model by representing the Hand Off Flow (HOF) requirements for the river, which is the legal requirement for all abstractors and an important component in water trading. Each abstractor on the river has their own HOF, which has been granted and is implemented in the model. For example, abstractor G (located at node 11 Fig. 2) cannot abstract if flows at Marham are less than or equal to 0.3 m^3/s, whereas abstractor D (node 6) cannot abstract if the flow at Marham is less than or equal to 1.07 m^3/s. The trading model was simulated using a weekly time-step, over which trades were optimized.

Three different scenarios were simulated:

- Scenario 1 (S1)- Baseline or existing: No trading, with environmental constraints (HOF)
- Scenario 2 (S2)- Trading: Trades are permitted with environmental constraints (HOF)
- Scenario 3 (S3)- Trading: Trades are permitted with the removal of environmental constraints (no HOF implemented).

S1 is the baseline which is the historical gauged flows and all results are compared to this. S2 and S3 represent the two trading scenarios (one with environmental constraints and one where they are removed). In S2 5 trades were predicted, while 7 were predicted in S3 where environmental constraints did not preclude trades.

2.3.2. Natural variability: synthetic flows

The ability to generate realistic daily streamflow sequences has been shown to be useful for management decisions (Augustin et al., 2008; Pender et al., 2016a,b). In order to estimate realistic daily stream flow time series, stochastic modelling is often used to generate synthetic flow sequences. Here we use a method proposed by Pender et al. (2016a). The model is a combination of the Hidden-Markov (HMM) and the generalised Pareto approach (GP). The combination of HMM and GP replicates the extremes of the series well therefore allowing the model to adequately encompass all flow conditions (Pender et al., 2016a). One hundred realisations of a 32-year time series were generated for the study catchment which had the same statistical attributes to the gauged flows (Fig. 3). Of these one hundred synthetic flow sequences, a sub-set of twenty were sampled (using a random number generator) to drive the habitat models (Table 2).

2.4. Analysis

In total the three different habitat models (*Salmo Trutta, Ranunculus Fluitans* and *Ephemeroptera Beraeidae)* were analysed for habitat suitability over the 32 year study period. When examining the results the combined analysis of the changes to species was important, as the added detail on food source and refugia allow analysis of the life cycle of brown trout (*Salmo Trutta*) and

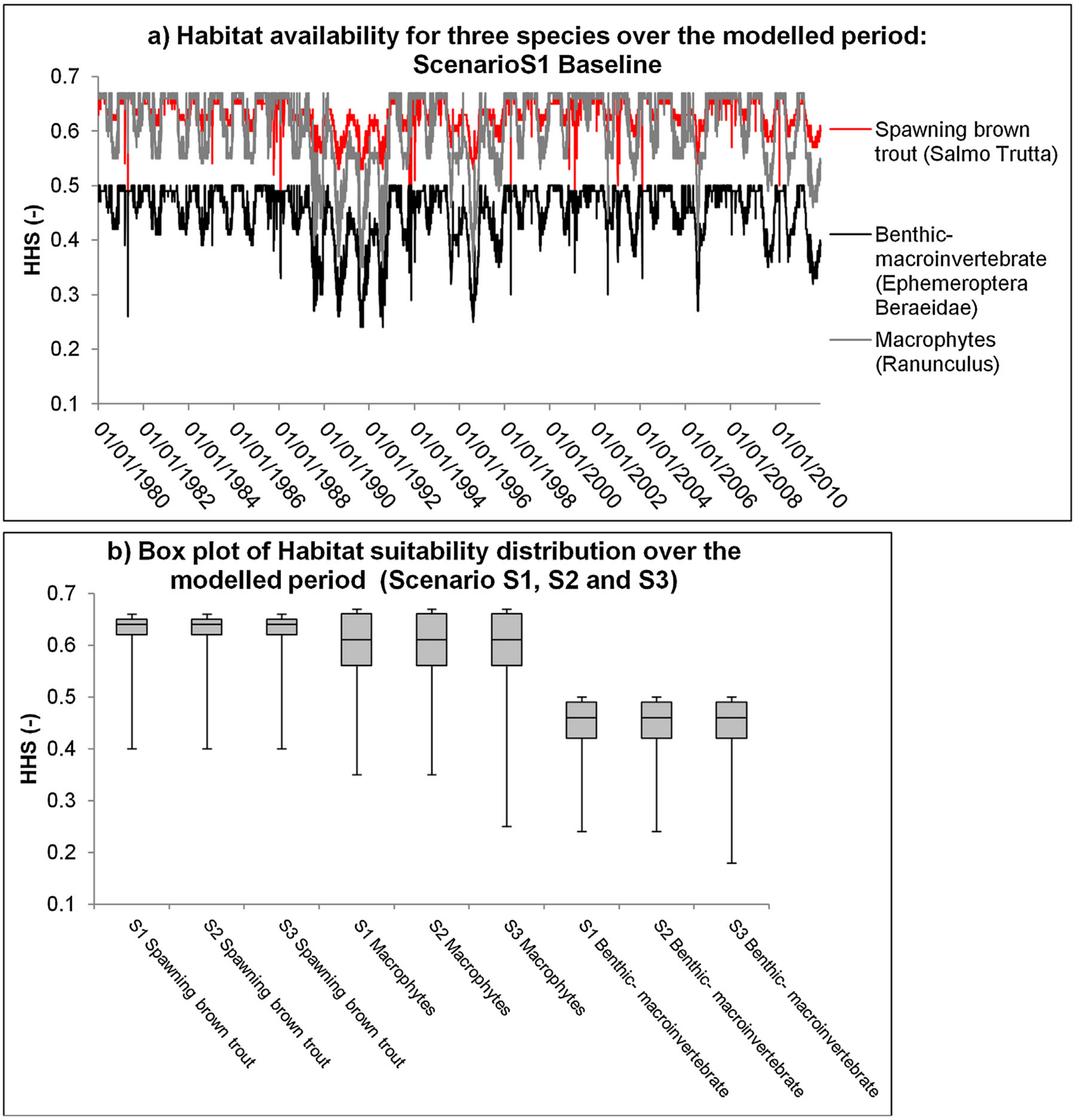

Fig. 4. (a) Baseline (S1) Habitat availability time series (HHS) results for three species (Spawning brown trout (*Salmo Trutta*)), Macrophytes (*Ranunculus Fluitans*) and Benthic macroinvertebrates (*Ephemeroptera Beraeidae*) and (b). Box plot distributions of habitat availability of each scenario (S1–S3).

not to consider hydraulic habitat in isolation. The models were run 23 times in total (21 flow sequences to represent current or existing conditions) and two different trading scenarios (with environmental constraints in place, and without). Two main outputs from CASiMiR were used for analysis:

- Hydraulic Habitat Suitability (HHS) (−) which is determined by dividing Weighted Usable Area (the reaches total habitat suitability related to a flow rate obtained by multiplying the area of each mesh cell by the SI value (WUA)) by the wetted area. This normalises results and allows comparisons between different sites. (Schneider et al., 2010). These were classified using a standard scale (Garbe et al., 2016) Table 3a.
- Spatial distributions of suitability Index (SI) (m^2) which provides information on the area available for each different habitat value on a scale from 0 (no habitat availability) to 1 (maximum habitat availability). These were classified using a standard scale (Garbe et al., 2016) Table 3b.

Firstly the results of S1–S3 were analysed in detail to expose significant differences as a result of trading flow perturbation. Each of the trading scenarios were compared to the baseline or existing flow regime and subsequent habitat availability (S1). Results were analysed on the HHS scale to determine the quality of the habitat availability in the study reach. The mean HHS for each species and corresponding HHS suitability scale was calculated (Table 3a) for each trading scenario. Mann- Whitney tests were carried out on each scenario for the whole series, as well as seasonally separated series, to determine if there were statistically significant different ($p < 0.05$) results between scenarios. Both annual and seasonal assessments were completed in order to investigate temporal variation in impact.

Using the spatial distribution (SI) of habitat availability (Table 3b), all species were compared for the wettest (2001), driest (1991) and average (1986) year recorded. Mann- Whitney statistical tests were conducted to compare scenarios and investigate the significance of any change in habitat availability ($p < 0.05$).

Table 4
Summary statistics of habitat availability.

	Spawning brown trout (Salmo Trutta)			Macrophytes: *Ranunculus*			Benthic-macroinvertebrate (Ephemeroptera Beraeidae)		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
Average	0.63	0.63	0.63	0.60	0.60	0.60	0.45	0.45	0.45
Median	0.64	0.64	0.64	0.61	0.61	0.61	0.46	0.46	0.46
Maximum	0.66	0.66	0.66	0.67	0.67	0.67	0.50	0.50	0.50
Minimum	0.40	0.40	0.40	0.35	0.35	0.25	0.24	0.24	0.18
95%ile	0.57	0.57	0.57	0.47	0.47	0.46	0.33	0.33	0.32
50%ile	0.64	0.64	0.64	0.61	0.61	0.61	0.46	0.46	0.46
5%ile	0.66	0.66	0.66	0.67	0.67	0.67	0.50	0.50	0.50
SD	0.03	0.03	0.03	0.07	0.07	0.07	0.05	0.05	0.06
Skew	−1.38	−1.35	−1.49	−0.88	−0.85	−1.22	−1.34	−1.30	−1.52
Kurt	2.38	2.25	2.55	0.35	0.24	1.75	1.42	1.29	2.28

Table 5
Mann- Whitney tests for significant change on the full time series (32 years) (HHS) boxes shaded grey indicate significant results.

		S1 to S2	S1 to S3
Spawning brown trout (*Salmo trutta*)	**Full**	0.472	0.015
	Winter	1	1
	Spring	0.376	0.238
	Summer	0.575	0
	Autumn	1	1
Benthic-macroinvertebrate (*Ephemeroptera Beraeidae*)	**Full**	0.493	0.021
	Winter	0.493	0.328
	Spring	0.493	0.328
	Summer	0.567	0
	Autumn	1	1
Macrophytes (*Ranunculus*)	**Full**	0.506	0.04
	Winter	1	1
	Spring	0.46	0.298
	Summer	0.585	0
	Autumn	1	1

Finally the synthetic flows were analysed; HHS was determined for each flow sequence and combined with the baseline (S1) scenario from above. These 21 realisations were then used collectively to demonstrate the natural variability in habitat availability that can be expected in the studied river. The anticipated distribution of potential HHS was analysed as a probability, and compared to the HHS as predicted in the two trading scenarios (S2 and S3).

3. Results and discussion

Firstly investigating the predictions by the trading model showed that; for S1 and S2 where environmental constraints are applied, there are very few occurrences of this being activated (i.e. the flow rarely gets low enough to trigger environmental constraints). Over the modelled period (1980–2011) a total of 13 weeks had environmental constraint activations (1990 = 3 weeks, 1991 = 7 weeks, 1992 = 1 week and 1996 = 2 weeks). Interestingly, the influence of trading measures did not affect the level of activation occurrences, and these remained constant between scenario S1 and S2. This suggests that implementing and encouraging a water market for the River Nar did not intensify water shortages in the catchment. This supports the theory of water markets, whereby it is anticipated that trading will allocate water more efficiently and equitably through the catchment (Erfani et al., 2015; Bjornlund, 2003) without exacerbating low flow instances.

3.1. Habitat model results for the baseline

The results (Fig. 4a and b and Table 4) show spawning brown trout and macrophytes have the highest levels of habitat availability in the reach followed by benthic macroinvertebrates. Macrophytes and benthic macroinvertebrates have fairly wide ranging results; macrophytes for example range between HHS 0.35–0.67, indicating that varying flows affect the available habitat to a large extent. Spawning brown trout (*Salmo Trutta)* has a mean HHS of 0.63 which corresponds to 'good' habitat suitability in this section of the river. This site is in the mid-reaches of the river and thus is expected to provide good conditions for spawning. Macrophytes (*Ranunculus Fluitans*) has 'good' habitat suitability (mean = 0.6), the area has abundant supplies of macrophytes including *Ranunculus* and provides good conditions for growth. Benthic macroinvertebrates have 'moderate' habitat suitability in this section of river (mean = 0.45). Species of mayfly were found at this site; however abundances were small in relation to sites upstream. From these results it is clear that conditions are favourable for brown trout (*Salmo Trutta*) in the reach, hydraulically as well as in terms of refugia and food provision.

3.2. Trading scenarios analysis

Comparison of the summary descriptive statistics for each of the trading scenarios (S1 baseline, S2 trading with environmental constraints and S3 trading with no environmental constraint) shows how trading affects the overall habitat availability in the studied reach (Table 4 and Fig. 4). The distribution between S1 and S2 is predominantly the same. Examining the boxplots (Fig. 4b) and the statistics indicates that the skew (asymmetry) and kurtosis (distribution of the tails) of the series change minimally which indicates the distribution of habitat availability is different. The skew slightly increases (e.g. Spawning brown trout S1 = −1.38, S2 = −1.35, benthic macroinvertebrates S1 = −1.34, S2 = −1.3) and the kurtosis value decreases (e.g. spawning brown trout S1 = 2.38, S2 = 2.25, Benthic macroinvertebrates S1 = 1.42, S2 = 1.29). Comparing S1 and S3 (where the environmental controls are removed), a more pronounced difference between distribution can be observed. For all species apart from spawning brown trout the minimum HHS value reduces. In summary, little change occurs as a result of trading with environmental constraint in place (S2), however once these are removed (S3), lower HHS values occur.

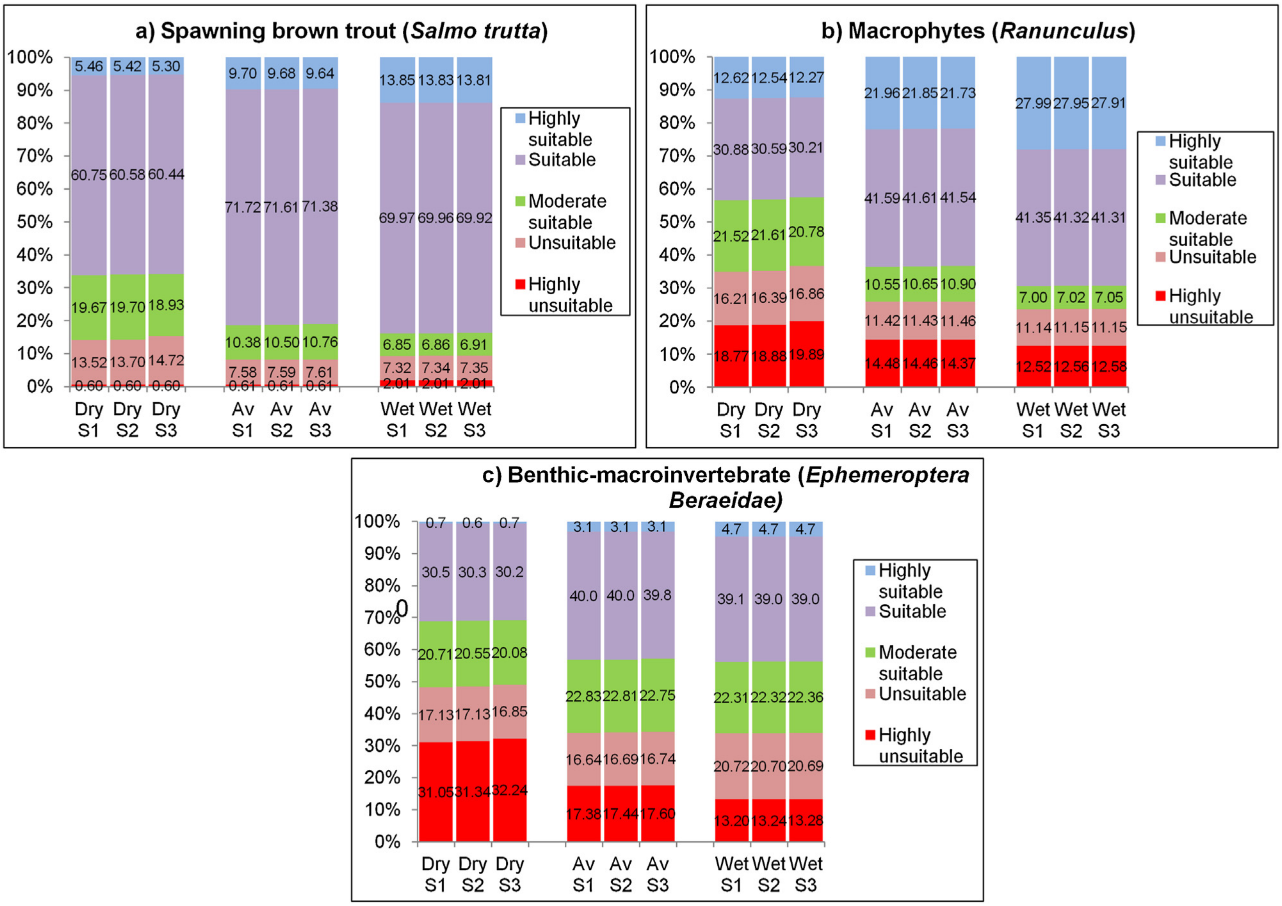

Fig. 5. Extreme year analysis (wet, dry, and average) of spatial habitat availability (SI) (S1–S3) for (a) Spawning brown trout (*Salmo Trutta*), (b) Macrophytes (*Ranunculus Fluitans*) and (c) Benthic macroinvertebrates (*Ephemeroptera Beraeidae*).

The Mann Whitney tests of statistical significance ($p < 0.05$) show that the change in habitat availability between the baseline and trading with environmental constraints scenarios are not statistically significant (Table 5). However when the constraints are removed (S1–S3), these changes become statistically significant over an annual test period. The method allows the examination of seasonal influences and this indicates that the change to habitat is only significant in the summer months. This is a logical conclusion as trading is only likely to occur when water supply is low. However what is critical is that no one species is differentially affected, and thus creating a great problem for its dependents upstream in the food web.

3.2.1. *Trading analysis of extreme years*

Change to habitat availability in the most extreme years (i.e. driest and wettest on record) was analysed in order to examine periods of extremes in depth. This analysis was completed using the SI values which provide information on the area available for each different habitat value, as opposed to the HHS which gives one overall value for the reach. The results are presented for each trading scenario (see Section 3.2.1) showing the percentage of time each habitat class occurs throughout each year (Wet = 2001, Average = 1986, Dry = 1991). For each year, and selected scenario, the length of time spent at each habitat suitability class is presented, therefore showing how the trading scenarios affect habitat availability for each species.

The results (Fig. 5) generally show that wet years provide better habitat for all species, with dry years providing the least amount of suitable habitat as anticipated. For macrophytes and benthic macroinvertebrate, the 'highly suitable' and 'suitable' habitat availability was highest in the wet year, and lowest in the dry year Likewise for macrophytes and benthic macroinvertebrate, the amount of highly unsuitable habitat was highest in the dry year and lowest in the wet year. For spawning brown trout however the amount of 'suitable' habitat was highest in the average year, and the amount of 'highly unsuitable' habitat was highest in the wet year. This is because spawning brown trout have a preference for lower flows but it is also related to its dependence on other biotic factors i.e. food and refugia (Garbe et al., 2016).

Generally for all species the occurrence of 'Highly suitable' and 'suitable' habitat was reduced in S2 compared to S1 and by slightly more in S3 (e.g. spawning brown trout, highly suitable, wet year: S1 = 13.85%, S2 = 13.83%, S3 = 13.81%). Similarly, the occurrence of 'Unsuitable' and most cases of 'highly unsuitable' habitat increases in S2 and increases by more in S3 (e.g. macrophytes, unsuitable, average year: S1 = 11.42% S2 = 11.43%, S3 = 11.46%). Again, what is important to note here is that no one species is affected disproportionately, and thus Brown Trout and the habitat it depends on (hydraulic, food sources and refugia) remain reasonably constant across scenarios.

The Mann-Whitney tests revealed few statistically different results between the trading scenarios (Table 6). No statistically significant differences in spatial habitat availability were found between S1 and S2 for any of the modelled species. Between S3 and S1 a few statistical differences were observed. For both macrophytes and spawning brown trout a statistical difference was found in the spatial availability of moderate habitat suitability for dry years. For both species the proportion of 'moderate' habitat suit-

Table 6
Mann-Whitney tests of significance for the extreme years, gray values indicate statistical difference.

		Spawning brown trout			Macrophytes			Benthic-macroinvertebrate		
		1986	1991	2001	1986	1991	2001	1986	1991	2001
Highly unsuitable	S1 to S2	0.624	0.732	0.942	0.852	0.604	0.707	0.905	0.461	0.739
	S1 to S3	0.138	0.395	0.855	0.371	0.084	0.656	0.749	0.213	0.687
Unsuitable	S1 to S2	0.979	0.667	0.792	0.754	0.736	0.831	0.758	0.815	0.995
	S1 to S3	0.654	0.348	0.723	0.344	0.472	0.936	0.59	0.459	0.805
Moderate	S1 to S2	0.787	0.892	0.834	0.777	0.925	0.733	0.541	0.732	0.84
	S1 to S3	0.42	0.016	0.658	0.412	0.038	0.646	0.031	0.395	0.78
Suitable	S1 to S2	0.683	0.732	0.875	0.791	0.732	0.888	0.796	0.732	0.945
	S1 to S3	0.355	0.395	0.841	0.428	0.395	0.801	0.434	0.395	0.716
Highly suitable	S1 to S2	0.787	0.732	0.903	0.787	0.732	0.903	0.796	0.879	0.918
	S1 to S3	0.42	0.395	0.85	0.42	0.395	0.85	0.434	0.879	0.811

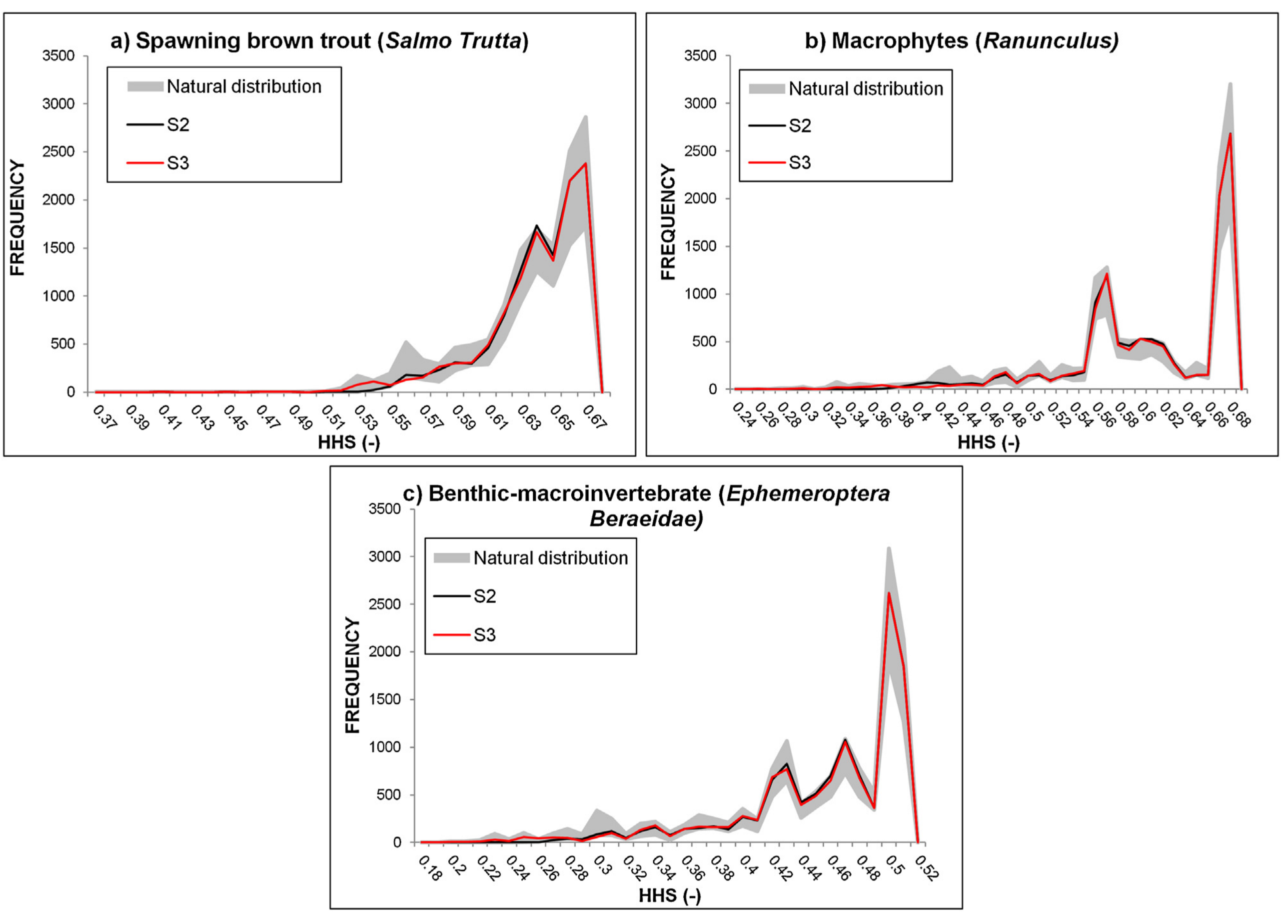

Fig. 6. Frequency plots of HHS across all 23 runs indicating the envelope of variation in results representing natural flow variability and highlighting the Trading runs (S2 and S3) for (a) Spawning brown trout (*Salmo Trutta*), (b) Macrophytes (*Ranunculus Fluitans*) and (c) Benthic macroinvertebrates (*Ephemeroptera Beraeidae*).

ability was significantly more (S3–S1), with an associated loss to 'Highly Suitable' and 'Suitable' habitat area (not statistically significant). For benthic macroinvertebrates, there was a significant reduction to 'moderate' habitat suitability area in the average year, with an associated gain to 'highly unsuitable' habitat areas (not significantly different). These results suggest that even in dry years the potential changes to habitat associated with trading are minimal in this catchment. Although without the environmental constraints these changes are slightly larger, and are statistically significant.

3.3. Natural variability and synthetic flows

In total twenty three different 32-year flow sequences were analysed using the habitat models. Twenty one flow sequences (S1 plus 20 synthetic) were considered to be variations on the baseline (statistically similar flow sequences, capturing the main properties and the extremes of the series (Table 2, Fig. 3)). Two 32-year flow sequences represent trading scenarios (S2 and S3). The frequency plots of HHS for all the flow sequences were plotted and combined, to capture the maximum and minimum predicted envelopes from this study (Fig. 6). This envelope indicates the potential variability in habitat availability (HHS: X axis) occurrence (frequency: Y axis), based on natural climatic and flow variation. Scenario S2 and S3 are plotted as solid lines within this envelope.

By observation and interpretation of these figures it is clear that the two trading scenarios are always within the natural distribution of HHS for each species and therefore trading is within the limits of natural variation of the river. This indicates that there may be flexibility in the response of this river to relax environmental constraints within the context of trading, in order to maximise potential water abstractions in periods of low flows.

4. Conclusions

In this study a novel approach to modelling water trading and its impacts on in-stream habitat has been proposed and tested for an over-abstracted chalk catchment in South East England. The methodology picks up trading impacts on the flow regime, and by using a synthetic flow generator places these changes (spatial and temporal) to the hydraulic regime into the context of natural flow variability. The variety of potential flow regimes were then simulated through a combination of habitat models, designed to capture a range of in-stream ecosystems, and a fuller picture of brown trout (*Salmo Trutta*) habitat. This methodology is flexible, adaptable and capable of capturing changes to in-stream ecosystems; and is transferable to other rivers both nationally (UK) and internationally.

In testing this methodology this research found that the effects of trading on the case study catchment were minimal to in-stream habitat availability and certainly within the range of natural variability. The environmental constraints that are in place adequately protect these habitats. However even without these constraints, these sensitive habitats seem to be largely protected. What it does show is that there may be flexibility in the system, which allows water to be used more cleverly through the catchment. These findings are useful and are an initial indication of the potential impacts of trading. However to expand these findings this methodology should be trialled across a greater variety of catchments and scales.

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Appendix A.

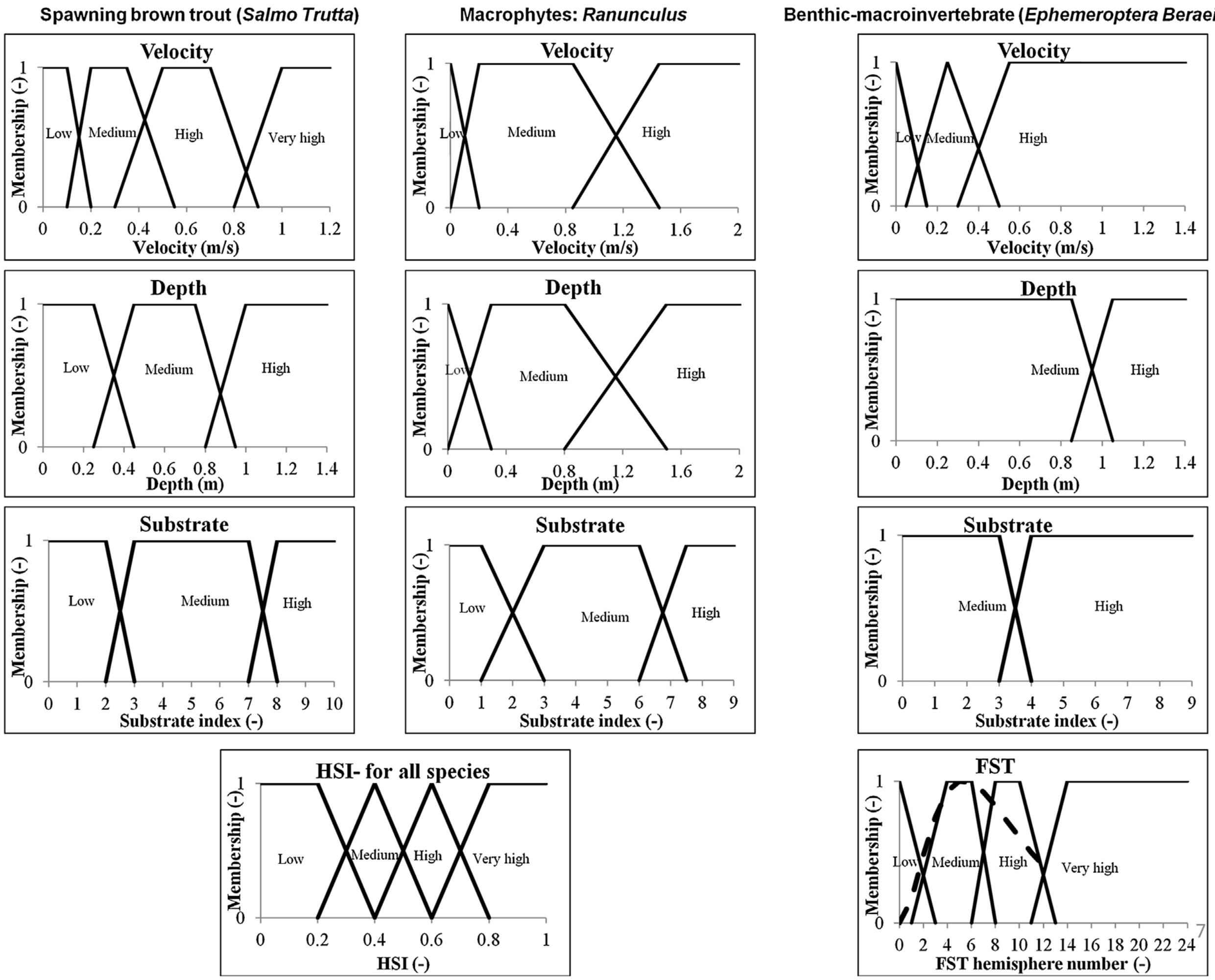
Fuzzy rules used for spawning brown trout (*Salmo Trutta*), macrophytes (*Ranunculus Fluitans*) and benthic macroinvertebrates (*Ephemeroptera Beraeidae*).

Parameter			Species		Parameter				
V	D	Sub	S Spawning BT	S Ran no cover	V	D	Sub	FST	S EB
H	H	H	L	L	L	M	M	L	L
H	H	M	M	M	L	M	M	M	M
H	H	L	L	L	L	M	M	H	L
H	M	H	L	M	L	M	M	VH	L
H	M	M	VH	H	L	M	H	L	M
H	M	L	H	L	L	M	H	M	H
H	L	H	L	L	L	M	H	H	M
H	L	M	VH	M	L	M	H	VH	L
H	L	L	H	L	L	H	M	L	L
M	H	H	L	L	L	H	M	M	L
M	H	M	M	M	L	H	M	H	L
M	H	L	L	L	L	H	M	VH	L
M	M	H	L	M	L	H	H	L	L
M	M	M	H	VH	L	H	H	M	M
M	M	L	H	M	L	H	H	H	L
M	L	H	L	L	L	H	H	VH	L
M	L	M	H	M	M	M	M	L	L
M	L	L	H	L	M	M	M	M	H
L	H	H	L	L	M	M	M	H	M
L	H	M	M	L	M	M	M	VH	L
L	H	L	L	L	M	M	H	L	M
L	M	H	L	L	M	M	H	M	VH
L	M	M	H	L	M	M	H	H	H
L	M	L	M	L	M	M	H	VH	L
L	L	H	L	L	M	H	M	L	L
L	L	M	H	L	M	H	M	M	L
L	L	L	M	L	M	H	M	H	L
VH	H	H	L	n/a	M	H	M	VH	L
VH	H	M	L	n/a	M	H	H	L	L
VH	H	L	L	n/a	M	H	H	M	H
VH	L	H	L	n/a	M	H	H	H	M
VH	L	M	M	n/a	M	H	H	VH	L
VH	L	L	L	n/a	H	M	M	L	M
VH	M	H	L	n/a	H	M	M	M	H
VH	M	M	M	n/a	H	M	M	H	M
VH	M	L	L	n/a	H	M	M	VH	L
					H	M	H	L	M
					H	M	H	M	VH
					H	M	H	H	H
					H	M	H	VH	L
					H	H	M	L	L
					H	H	M	M	M
					H	H	M	H	L
					H	H	M	VH	L
					H	H	H	L	M
					H	H	H	M	H
					H	H	H	H	M
					H	H	H	VH	L

V = velocity, D = depth, Sub = substrate, S = suitability, BT = brown trout, Ran = Ranunculus, EB = Ephemeroptera Beraeidae, H = high, M = Medium, L = Low, VH = Very high.

Appendix B.

Fuzzy sets used for spawning brown trout (*Salmo Trutta*), macrophytes (*Ranunculus Fluitans*) and benthic macroinvertebrates (*Ephemeroptera Beraeidae*).The HSI fuzzy set was the same for each species. The curve in the FST fuzzy set for food represents the FST curve to demonstrate how the fuzzy sets correspond to it.



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